High-Current Thin-Film Multijunction Thermal Converters and Multiconverter Modules

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***Abstract*—High-current, thin-film multijunction thermal converters (FMJTC's) have been fabricated at NIST with heater ranges from a few milliamperes to 1 A. Multiconverter modules containing high-current FMJTC's have also been constructed to measure currents up to 6 A at frequencies up to 100 kHz.**

I. Introduction

THE National Institute of Standards and Technology (NIST) reference thermal current converter standards are a set of thermoelements (TE's) rated from 2.5 mA to 20 A [1], [2]. For ranges up to 250 mA, the TE's are vacuum-enclosed with a single thermocouple attached to the midpoint of a short, relatively straight heater by an insulating bead.

The converters rated at 250 mA and above contain temperature compensation, heat sinks attached to the heaters, and low-inductance current-return paths. The highest current units also have tubular heaters. This construction provides a reasonably low reactance and moderate skin effect. The output emfs of these devices generally range from about 7 mV to 12 mV at their rated input current. Although traditional TE's in the current range of 250 mA and below have small ac–dc differences which are reasonably independent of frequency, higher current, conventional TE's may exhibit large errors from skin effect in the heater and lack of suitable thermal lagging or compensation. The specially constructed high-current TE's in use at NIST are no longer commercially available, and attempts to rebuild failing units have been only partially successful. Current shunts can be used, but they present more problems from stray impedances to ground and thermal drift, and exhibit greater errors from skin effect at 20 kHz and above.

For these reasons, high-current, thin-film multijunction thermal converters (FMJTC's) have been designed and fabricated. The design and fabrication techniques permit operating currents up to 1 A in a single chip. This paper reports on the fabrication and performance of these high-current FMJTC's and on the construction and results from multiconverter modules containing up to six of these high-current FMJTC's.

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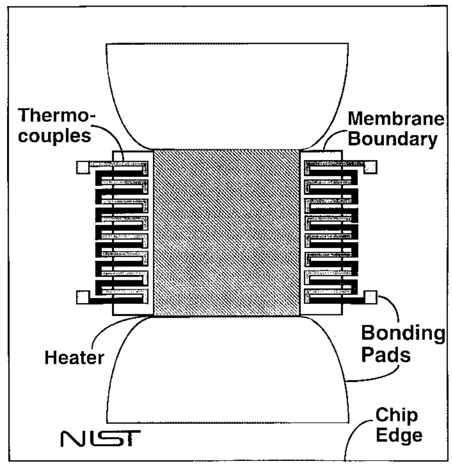


Fig. 1. Geometric outline of a high-current FMJTC. The heater is approximately 1 mm × 1 mm.

II. Design Considerations of High-Current FMJTC's

A primary source of error in high-current TE's is skin effect arising from the relatively thick heater structures. To minimize this error, the heater structure of the high-current FMJTC's is less than 1 μm thick and composed of either aluminum, constantan, or Evanohm,[1] sputtered on to a silicon wafer using fabrication methods described in earlier publications [3], [4].

The distributed inductance and capacitance of the TE heater structure may also result in significant contributions to the ac–dc difference of the device. To overcome this error, the heaters of the high-current FMJTC are quite short—some as short as 1 mm. A geometric outline of a high-current FMJTC intended for currents up to 1 A is shown in Fig. 1. This geometry, made possible by photolithography technology, results in a heater with much less inductance than that of a traditional TE. Thermal drift is minimized in the new high-current FMJTC's by providing good thermal contact with their alumina mounting substrates. They are small and lend themselves to coaxial geometry providing improved ac current definition and reduced sensitivity to the proximity of other conductors. The FMJTC chips have membrane sizes ranging from approximately 1 mm × 2 mm to 2 mm × 4 mm and

[1] The use of trade names in this paper does not imply endorsement or recommendation by NIST.

TABLE I
AC–DC DIFFERENCES FOR A SINGLE REPRESENTATIVE, EVANOHM-HEATER HIGH-CURRENT FMJTC MOUNTED IN THE MULTICONVERTER MODULE

Heater Resistance	Thermocouple Resistance	Number of Couples
18.2 Ω	1.35 kΩ	8/side, 16 total

Applied Current	Output emf	Ac-dc Difference (μA/A)						
mA	mV	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
20	6.4	+1±7	+3±7	+4±7	+5±7	+8±9	+18±11	+18±21
100	141.1	+64±7	+8±7	0±7	+1±7	+4±10	+6±11	-13±32

TABLE II
AC–DC DIFFERENCES FOR A SINGLE REPRESENTATIVE, ALUMINUM-HEATER HIGH-CURRENT FMJTC MOUNTED IN THE MULTICONVERTER MODULE

Heater Resistance	Thermocouple Resistance	Number of Couples
0.3 Ω	1.04 kΩ	8/side, 16 total per chip

Applied Current	Output emf	Ac-dc Difference (μA/A)						
A	mV	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
1	6.8		-77±7	-8±7	-3±7	+1±10	-10±13	-36±43
2	32.0		-283±8	-24±8	-11±8	-10±10	-22±14	-44±47

TABLE III
AC–DC DIFFERENCES FOR THREE ALUMINUM-HEATER HIGH-CURRENT FMJTC'S MOUNTED IN MULTICONVERTER MODULE

Module Heater Resistance	Thermocouple Resistance	Number of Couples
0.2 Ω	6.24 kΩ	8/side, 16 total per chip

Applied Current	Output emf	Ac-dc Difference (μA/A)						
A	mV	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
1	2.1	-32±7	-10±7	-2±7	+2±7	+8±10	+7±13	-32±43
3	19.7		-72±9	-2±9	-1±9	+3±12	-8±17	-50±52

overall chip dimension from 6 mm × 6 mm to 6 mm × 7 mm. The alumina substrates are approximately 2 cm square.

Because of the thin isothermal membrane supporting the heater structure, the high-current FMJTC is much more efficient than wire TE's. The voltage drop across the 0.3 Ω high-current FMJTC heater is of the order of tens of millivolts, rather than the 0.15 V to 1 V drop of traditional thermal current converters or shunts. There is therefore much less self-heating in the high-current FMJTC, and drift-related errors introduced by heating of the structure are minimized. The low thermal conductance of the thin membrane and the use of twenty thermocouples increase the output emfs to about 20 mV at nominal input current. To further reduce the inductance, aluminum tracks (not shown in the diagram), which may be connected to ground, are deposited on the silicon. For the highest current levels, the chips are mounted with three gold wire-bonded ribbons carrying the heater current.

Three different metals have been used for the high-current FMJTC heaters to provide different current ratings. Devices with Evanohm heaters have been tested up to 100 mA, while aluminum heaters have been tested up to 1 A. Both heaters can withstand a 200% overload for a few minutes.

III. MULTICONVERTER MODULE

Up to six thin-film multijunction thermal converters can be mounted in parallel in a newly constructed multiconverter module. A cutaway diagram of the high-current module is shown in Fig. 2 and a top view is given in Fig. 3. The outside diameter of the cylinder is approximately 12 cm and the height is approximately 7 cm. The module is suitable for holding a matched set of FMJTC's with coaxial heater geometries of any current rating up to several amperes. In order to maintain a constant temperature environment, the alumina substrates of the FMJTC's are fixed to brass frames to provide good thermal lagging. The input and output leads from each FMJTC chip are electrically isolated from the frame through brass end blocks mounted on dielectric material. The current input to the devices is paralleled through a symmetric six-fingered, star-shaped structure, and their thermocouple outputs are connected in series-aiding.

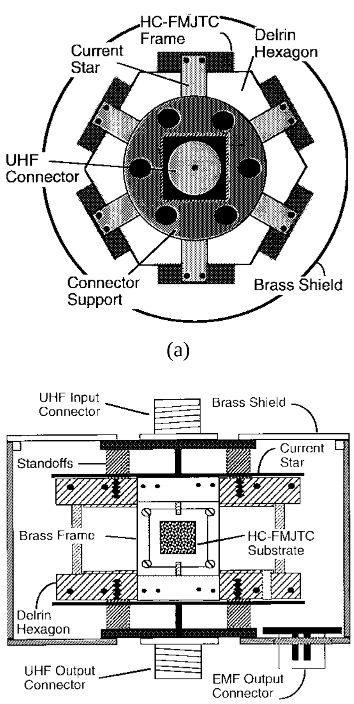
The FMJTC frames are mounted on a hexagonal structure made of Delrin, a low-loss dielectric material, and the assembly positioned inside a cylindrical brass housing to preserve coaxial symmetry. In order to reduce the variability of stray impedances, to better define the ac–dc difference of the converters and to keep the ac voltage drop across the module at higher frequencies close to the voltage drop on dc, the module is designed to be completely coaxial. Input and output connectors permit the module to be used in a three-terminal, coaxial configuration in series with another current converter (Fig. 3). If one of the coaxial connectors is shorted, the module can be connected in the conventional configuration. The effect of shunt capacitance from the inner structure to the outer shell is small because the impedance of the current-carrying circuit is very low. In addition, the

TABLE IV
AC–DC DIFFERENCES FOR SIX ALUMINUM-HEATER HIGH-CURRENT FMJTC'S MOUNTED IN MULTICONVERTER MODULE

Module Heater Resistance		Thermocouple Resistance			Number of Couples			
0.2 Ω		13.97 kΩ			8/side, 16 total per chip			
Applied Current	Output emf	Ac-dc Difference (µA/A)						
A	mV	400 Hz	1 kHz	5 kHz	10 kHz	20 kHz	50 kHz	100 kHz
2	4.2	-44±8	-8±8	-4±8	-10±8	-10±10	-31±14	-205±47
6	40.5	-402±10	-78±10	-5±10	-2±10	-7±17	-52±21	-309±66

TABLE V
AC–DC DIFFERENCES FOR SIX, EVANOHM-HEATER FMJTC'S WITH NOMINALLY 5 mA HEATER RATINGS MOUNTED IN THE MULTICONVERTER MODULE

Module Heater Resistance		Thermocouple Resistance			Number of Couples		
18.8 Ω		75.60 kΩ			varied		
Applied Current	Output emf	Ac-dc Difference (µA/A)					
mA	mV	100 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10	9.8	+2±7	+1±7		+1±9	+5±11	+8±21
30	96.5	+10±7	+7±7	+7±7	+4±9	+6±11	-5±24
50	224.4	+28±7	+1±7	+3±7	+1±9	+4±11	-1±27
100	930.0		+8±7		-3±10	-2±11	-22±32



(a)

(b)

Fig. 2. (a) Top view of the multiconverter module. (b) Cutaway side view of the multiconverter module. The outside diameter of the cylinder is approximately 12 cm and the height is approximately 7 cm.

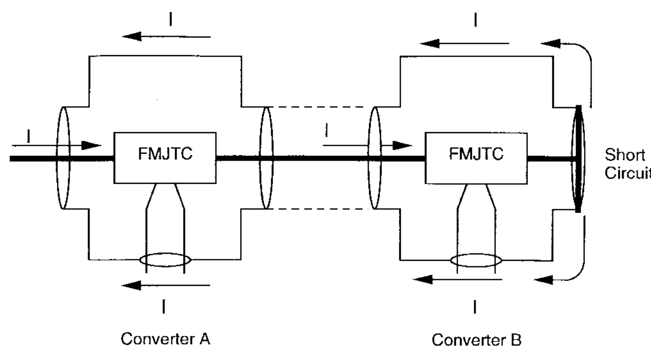


Fig. 3. Two coaxial converter modules connected in series. Converter A is shown in the three-terminal, or coaxial through, connection. Converter B is shown in the two-terminal connection.

capacitance itself is minimized by maintaining a spacing of several millimeters between structures and by keeping most of the dielectric material interior of the central current path. Possible contributions to ac–dc difference also arise from the connection of thermal converter heaters in parallel, since currents may not divide between the converters in the same ratios on ac as on dc. One possible mechanism for different current division on ac and dc is the existence of reactance in the parallel current paths. If the current in one converter path is I_{j}, its dc resistance is R_{j}, and its impedance is Z_{j}, then the dc current in that path is $I_{\mathrm{j}}^{\mathrm{dc}} \propto (R_{\mathrm{j}})^{-1}$. The ac current in that path, however, is $I_{\mathrm{j}}^{\mathrm{ac}} \propto (Z_{\mathrm{j}})^{-1}$. Since the measured ac–dc differences with one chip in the module show results within a few μA/A as for groups of chips, and since this is true even for low-resistance heaters, the imbalance between ac and dc current due to reactance in the module appears quite small. A second mechanism for the production of ac-dc difference due to paralleling is the possibility of mismatched thermoelectric effects in the leads. With such large currents flowing in the heater circuit, thermal or thermoelectric effects (such as Peltier heating) can differ from chip to chip and produce level dependent but frequency independent ac–dc differences. In fact, ac–dc differences that are dependent on heater power but that are frequency independent have been observed on chips which are believed to have flawed contacts between metals.

For properly made chips, however, such effects have been quite small.

IV. RESULTS

Existing chip designs and the existing multiconverter module permit ranges up to 6 A. Preliminary results of ac–dc difference tests on high-current FMJTC's are shown in Tables I and II, along with estimated uncertainties for the measurements. Because these devices have not been extensively measured, these uncertainties, based on preliminary data, may not reflect their long-term performance. The data in the tables are given with the conventional definition where a plus sign indicates that more ac than dc signal was required to produce the same output level. AC-DC differences and estimated uncertainties for groups of FMJTC's mounted in the multiconverter module are given in Tables III–V. The ac–dc differences for the FMJTC's as single chips or mounted in groups in the multiconverter module are generally comparable to, and sometimes smaller than, traditional thermoelements at similar current levels. Although some variation in the ac–dc difference is observed at frequencies of 1 kHz and above, the performance of the FMJTC's over a current range of 10 : 1 makes them good candidates for current buildup measurements in that frequency range. At frequencies below 1 kHz, low-frequency compensation [5] on the individual converters and in the multiconverter module can be used to improve the low-frequency error arising from the very short time constants, about 20 ms, on the high-current chips. New chip geometries, with inherently longer time constants, are also under development to improve the low-frequency performance, but a greater increase in the time constant, and therefore improvement in the low-frequency performance, is obtained from mounting the chips in vacuum. Vacuum headers are under development and will be used for routine mounting. With time constants longer than 200 ms, variations with current level at frequencies down to 100 Hz will be small enough to enable current buildup measurements over the full useful range of the converters. Additional modules to provide ranges up to 20 A are also under development.

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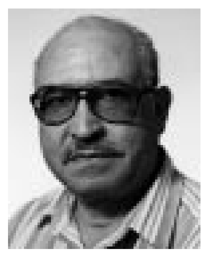
Joseph R. Kinard (S'69–M'71–SM'80), for a photograph and biography, see this issue, p. 228.

Thomas E. Lipe (M'94), for a photograph and biography, see this issue, p. 351.



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Donald B. Novotny (M'62–SM'77–F'87), for a photograph and biography, see this issue, p. 351.

De-Xiang Huang, for a photograph and biography, see this issue, p. 341.